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ABSTRACT

Tests were run with 20-mm bore angular-contact ball bearings at 400° and 450° F (477 and 505 K) to determine the effects of oxygen concentration on the oxidation of an advanced Type II ester. The bearings were run at 10 600 rpm and 70-pound thrust load. Oxygen content of the gas in the bearing chamber was varied from less than 0.1 percent to approximately 21 percent by volume. Increases in bearing torque, lubricant viscosity, and acid number were used as indicators of lubricant oxidation and degradation. The advanced ester exhibited less oxidation than did a synthetic paraffinic oil under similar test conditions. A time limitation (induction period) on the effectiveness of the oxidation inhibitor in the ester was indicated.

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SUMMARY

Tests were run with 20-mm bore angular-contact ball bearings at 400° and 450° F (477 and 505 K) to determine the effects of oxygen concentration of the atmosphere in the bearing chamber on the oxidation of an advanced Type II ester. The bearings were run at 10 600 rpm and 70-pound (310 N) thrust load which produced a maximum Hertz stress of 200 000 psi (1.38×10^{9} N/m^{2}) at the inner race. Oxygen content of the gas in the bearing chamber was varied from less than 0.1 percent to approximately 21 percent by volume. Increases in bearing torque, lubricant viscosity, and acid number were used as indicators of lubricant oxidation and degradation.

There was insignificant oxidation of the advanced ester in 6-hour tests at a 400° F (477 K) outer-race temperature up to a 21-percent oxygen concentration. However, at a 21-percent oxygen concentration at 400° F (477 K), a significant increase in oxidation rate occurred after 25 hours of operation suggesting a time limitation (induction period) of the oxidation inhibitor in this fluid. At 450° F (505 K) in 6-hour tests, a general trend toward increased oxidation of the ester with increased oxygen concentration was noted.

The ester exhibited much less oxidation in 6-hour tests than a synthetic paraffinic oil with an oxidation inhibitor for all oxygen concentrations at 450° F (505 K) and at oxygen concentrations greater than 8 percent at 400° F (477 K).

Based on preliminary elastohydrodynamic film thickness measurements and post-test bearing surface examination, elastohydrodynamic lubrication was the predominant mode of lubrication throughout the range of test conditions.

INTRODUCTION

Bearing temperatures in the range of 400° to 600° F (477 to 588 K) are anticipated in advanced gas turbine engines and accessory drive systems such as those related to high performance supersonic aircraft (refs. 1 and 2). A reliable bearing-lubricant system is required for these and other high-temperature, high-speed applications. The key to successful and reliable bearing operation at these conditions is selection, or if necessary, the development of a lubricant that will withstand these difficult environments.

New classes of liquid lubricants have been developed recently for extending the upper

temperature limits of liquid lubricants (refs. 3 to 6). These new lubricants have been studied to determine their thermal stability, their oxidation and corrosion properties, their effect on rolling-element fatigue, and their elastohydrodynamic (EHD) film forming capabilities (refs. 2 to 11). These parameters define the lubricant's upper temperature limitations.

A class of lubricants of interest in the temperature range from 400° to 450° F (477 to 505 K) is the advanced Type II ester. One such fluid is a tetra-ester which has shown promise in bearing tests in this temperature range (information obtained from E. N. Bamberger of General Electric Co., Cincinnati, Ohio). This lubricant has good thermal and oxidative stability to 425° F (491 K).

Reference 12 shows the effects of oxygen concentrations from less than 0.1 percent to 21 percent by volume on the oxidation of a synthetic paraffinic oil both with and without an oxidation inhibitor in bearing tests from 400° to 500° F (477 to 533 K). The oxidation inhibitor was effective at 400° F (477 K) for a limited time (induction period), but at 450° F (505 K), it offered no advantage. In general, oxidation of the uninhibited synthetic oil increased as oxygen concentration increased.

These tests (ref. 12) also demonstrated the feasibility of studying lubricant oxidation in short term bearing tests using bearing torque as an indication of lubricant oxidation. Bearing torque increase was a result of lubricant viscosity increase due to lubricant oxidation.

The objective of the research reported herein is to determine the effects of variable oxygen content on the degradation of the advanced ester lubricant in bearing tests at 400° and 450° F (477 and 505 K). In order to accomplish this objective, tests were performed with 204-size angular-contact ball bearings at temperatures up to 450° F (505 K) with a recirculating type lubrication system. Test conditions included an inner-race speed of 10 600 rpm and a thrust load of 70 pounds (310 N) producing a maximum Hertz stress at the inner-race-ball contact of 200 000 psi (1.38×10^9 N/m^2). Bearing torque increase, viscosity increase, and total acid number were used as indicators of lubricant degradation. Preliminary measurements were made of EHD film thickness with this lubricant in a crowned-coned disk apparatus.

APPARATUS AND PROCEDURE

Bearing Test Apparatus

The high-temperature bearing test apparatus is shown in figures 1 and 2. The heated bearing housing is supported by an externally pressurized gas bearing to allow torque measurement with a strain-gage force transducer.

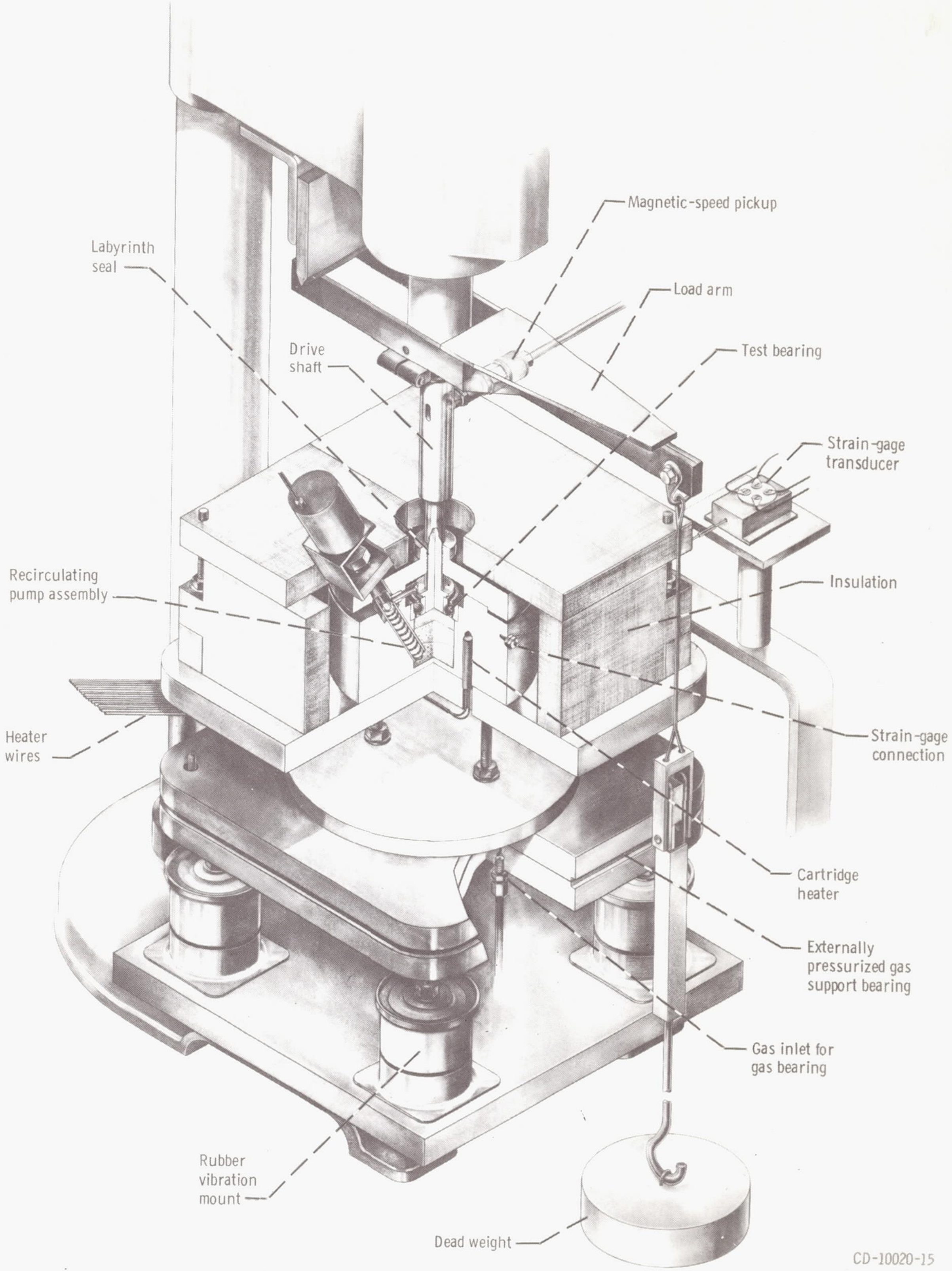


Figure 1. - High-temperature bearing test apparatus.

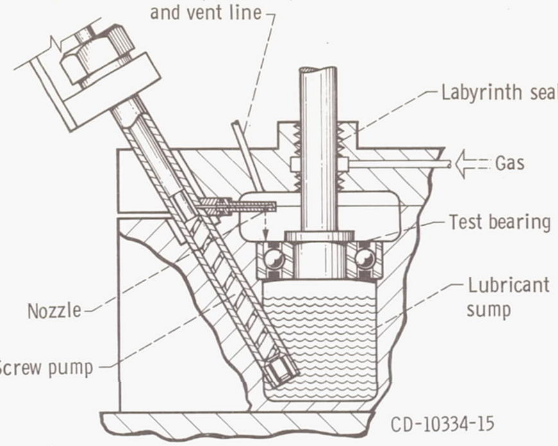


Figure 2. - Test bearing and lubricant recirculating pump.

The test lubricant is recirculated from the sump through the test bearing by means of a screw pump. A single nozzle directs the lubricant stream at the space between the bearing retainer and the counterbored outer race (fig. 2). Lubricant flow rate is calibrated and controlled by pump motor speed.

The atmosphere in the test bearing chamber was controlled by a nitrogen-gas-air mixture introduced at the labyrinth shaft seal (fig. 2). This atmosphere was continuously sampled and analyzed for oxygen content with a paramagnetic oxygen analyzer with a sensitivity of 0.1 percent. Gas flow through the bearing chamber was about 2 cubic feet per hour (940 cm^3/min).

Critical temperatures were measured with thermocouples at several locations: the outside diameter of the outer race, the ambient gas in the test bearing chamber, the bulk lubricant in the sump, and the pump housing. A more detailed description of this tester can be found in reference 12.

Procedure

Each bearing to be tested was cleaned with solvent, dried, and installed in the test apparatus. An initial charge of 40 cubic centimeters of test lubricant was added to the lubricant sump. The test chamber was purged with nitrogen gas (~34 ppm O_2) as the heaters were energized and during warmup to test temperature. When an outer-race temperature of 300° F (422 K) was reached, a lubricant flow rate of 5 cubic centimeters per minute was started, the test load was applied, and the apparatus motor was started. When the test temperature was reached, the desired atmosphere (oxygen percentage) was introduced, and the lubricant flow rate was increased to 14 cubic centimeters per minute.

This flow rate was constant for all tests reported herein. During each test, bearing torque, oxygen content in the test-bearing chamber, and outer-race temperature were recorded on strip-chart recorders. Lubricant flow rate (pump rpm), and test chamber ambient gas temperature were periodically recorded. Test duration was 6 hours at the desired test temperature unless otherwise specified.

After a test, the bearing was removed and inspected for surface appearance and deposit formations. The lubricant sample was carefully removed and analyzed. Viscosity at 100° and 210° F (311 and 372 K) and total acid number (mg KOH per gm oil) were measured.

MATERIALS AND LUBRICANTS

Test Bearings

The bearings used in these high-temperature lubrication tests were 204-size (20-mm bore) angular-contact ball bearings of ABEC-5 specifications. The material of the balls and races was vacuum-melted AISI M-1 steel of Rockwell C hardness 63±1. The retainer was of the machined inner-land riding type made from annealed AISI M-1 material. Further specifications of the test bearings are as follows:

Ball diameter, in. (cm)	9/32 (0.715)
Number of balls	10
Contact angle, deg	17±1
Conformity, percent	
Inner race	53
Outer race	54
Internal radial clearance, in. (cm)	0.0017 (0.0043)

Advanced Type II Ester

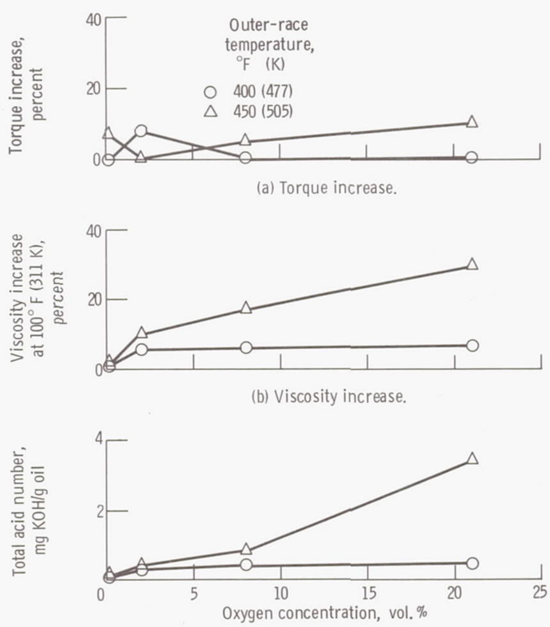
This lubricant is a tetra-ester base oil containing additives which include oxidation and corrosion inhibitors and an antiwear additive. This fluid has shown good operating potential in limited bearing tests at temperatures to 425° F (491 K) in an air environment (information obtained from E. N. Bamberger of General Electric Co., Cincinnati, Ohio). The viscosities of this lubricant at 100°, 210°, and 450° F (311, 372, and 505 K) are 29.0, 5.4, and 1.2 centistokes (extrapolated) (29.0×10^{-6}, 5.4×10^{-6}, and 1.2×10^{-6} m^2/sec), respectively.

RESULTS AND DISCUSSION

Six-Hour Bearing Tests

A series of bearings was run with the Type II ester at outer-race temperatures of 400^{o} and 450^{o} F (477 and 505 K). Oxygen concentration was varied from less than 0.1 percent to approximately 21 percent by volume. Results of these 6-hour tests showing bearing torque increase, viscosity increase, and total acid number after test are given in figure 3.

The torque increase shown in figure 3(a) is the percentage of increase in torque from the beginning to the end of each 6-hour test. Percent torque increase was used to compare the results, since each test at a particular condition was made with a new bearing. Initial bearing torque for new bearings varied from approximately 0.04 inch-pound to 0.07 inch-pound (0.0045 N-m to 0.0079 N-m). Although lubricant oxidation could conceivably result in decreased lubricant viscosity and decreased bearing torque, such effects were not noted in these 6-hour tests. Viscosity and torque either remained the same as the initial values or increased as shown in figure 3. Increases in torque, viscosity, and acid number are greater, in general, at 450^{o} F (505 K) than at 400^{o} F (477 K) outer-race temperatures. At 400^{o} F (477 K) the data show very little effect of oxygen concentration.



(c) Total acid number.

Figure 3. - Effect of oxygen concentration on advanced ester after 6-hour bearing tests. Bearing type, 20-millimeter bore angular-contact ball bearing; bearing material, AISI M-1; inner-race speed, 10 600 rpm; thrust load, 70 pounds (310 N).

At 450° F (505 K) outer-race temperature, a general trend toward increased oxidation or lubricant degradation is apparent as oxygen concentration increases.

The results at 400° F (477 K) with the ester are very similar to those with the synthetic paraffinic oil with the oxidation inhibitor (ref. 12) at 400° F (477 K) up to oxygen concentrations of about 8 percent. With this exception the ester shows much less effect of oxygen concentration on lubricant degradation at 400° and 450° F (477 and 505 K) than does the synthetic paraffinic oil both with and without an oxidation inhibitor (ref. 12).

Time Effect on Lubricant Oxidation

A bearing test was run with the advanced ester for 26 hours at an outer-race temperature of 400° F (477 K) and an oxygen concentration of 8 percent. No bearing torque increase was detected during the test. Another test at 400° F (477 K) and 21-percent oxygen concentration was run for 50 hours. Results of this test are shown in figure 4. At approximately 25 hours, an abrupt rise in the torque-increase curve occurred, after which the torque increased at a much higher rate. As with the synthetic paraffinic oil (ref. 12), this break apparently represents the point at which the oxidation inhibitor in the ester is no longer effective, after which oxidation proceeds at a higher rate. This induction period (time period before the break) would undoubtedly be changed with changes in bearing operating conditions. Also shown in figure 4 as a broken line are the results from a 6-hour test (ref. 12) with the synthetic paraffinic oil containing an oxidation inhibitor at an outer-race temperature of 400° F (477 K) and an oxygen concentration of 21 percent. The advantage that the advanced ester has when compared to the synthetic paraffinic oil in an air environment at 400° F (477 K) is apparent.

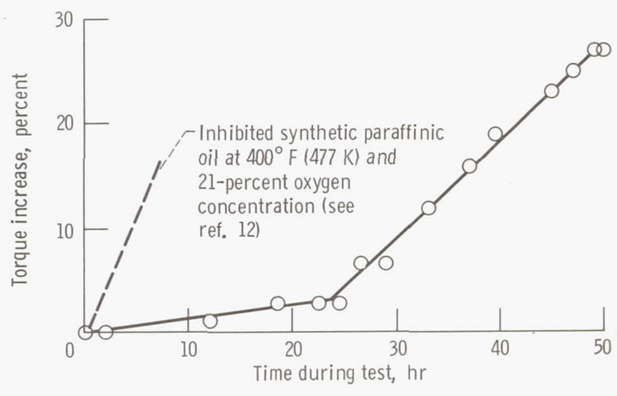


Figure 4. - Torque increase during 50-hour test with advanced ester. Bearing type, 20-millimeter bore angular-contact ball bearing; bearing material, AISI M-1; inner-race speed, 10 600 rpm; thrust load, 70 pounds (310 N); outer-race temperature, 400° F (477 K); oxygen concentration, 21 percent by volume.

Preliminary Elastohydrodynamic (EHD) Measurements

Preliminary EHD film thickness measurements were made with the synthetic paraffinic oil used in reference 12 and the advanced ester in a modified rolling-disk machine described in reference 13. This apparatus shown in figure 5 uses crowned-coned disks (fig. 6) to simulate the ball-race contact in an angular-contact ball bearing. (The geometry used in these tests simulate the ball-race contact in a 120-mm bore angular-contact ball bearing. A disk speed of 26 000 rpm simulates a bearing speed of 12 000 rpm.) The lubricant film thickness is measured by directing high energy X-rays between the two disks. The amount of X-rays passing between the disks is related to the thickness of the lubricant film separating the surfaces. The disks are operated in a nitrogen atmosphere to prevent oxidation of the lubricant.

The results of these preliminary measurements are shown in figure 7. These data indicate that the film thickness at 450° F (505 K) with the synthetic paraffinic oil is slightly greater (about 1 μin. (2.5 μcm)) than that with the advanced ester. These measured film thicknesses (i.e., 5 to 7 μin. (13 to 18 μcm)) in this range of test conditions, suggests that EHD lubrication would be the predominant mode of lubrication in the bearing tests reported herein. At 450° F (505 K), the viscosities of the synthetic paraffinic oil and the advanced ester are approximately 4.3 and 1.2 centistokes (4.3×10^{-6} and 1.2×10^{-6} m^2/sec), respectively.

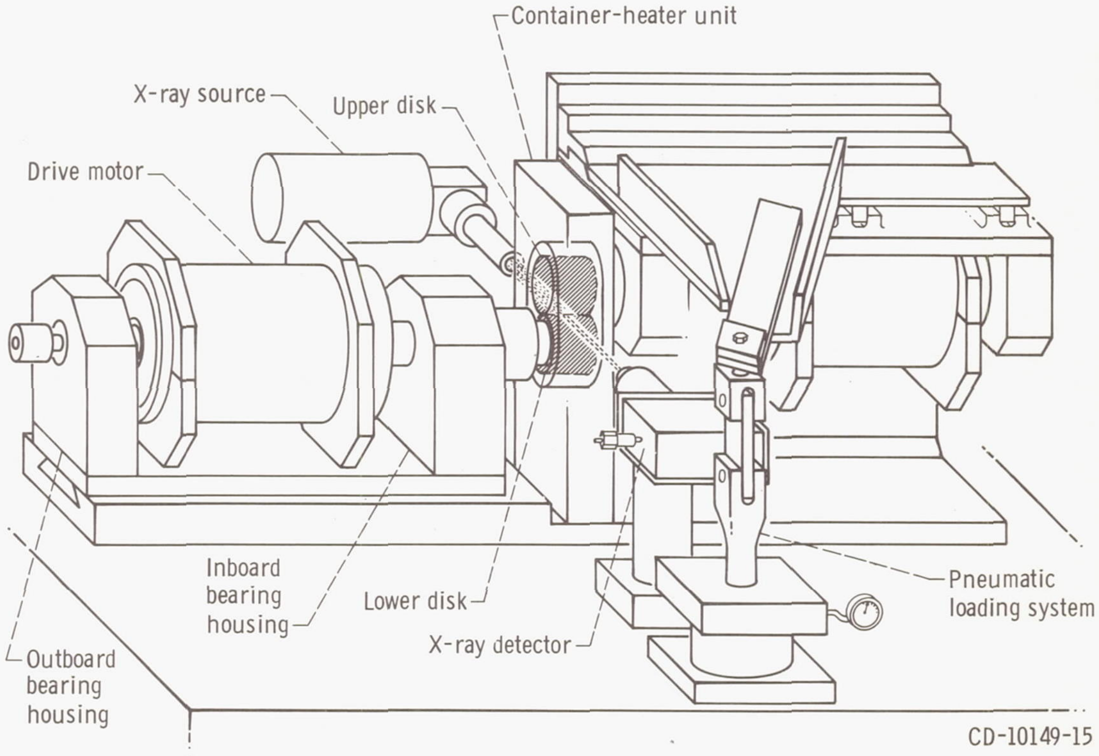


Figure 5. - Rolling-contact disk machine.

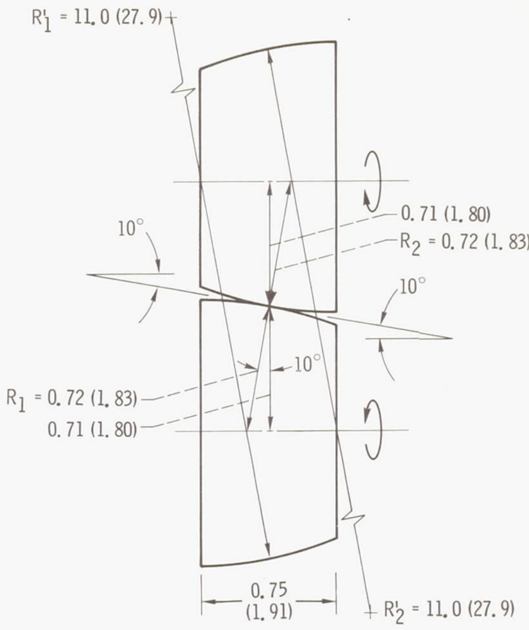


Figure 6. - Contacting disk geometry. (All linear dimensions are in inches (cm).)

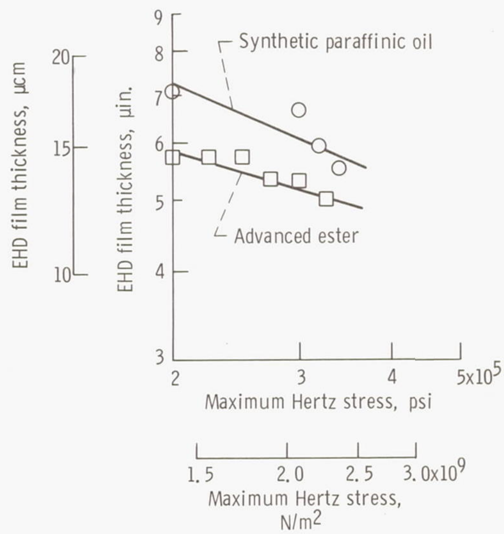


Figure 7. - Preliminary elastohydrodynamic film thickness in rolling-disk apparatus using crowned-coned disks. Disk temperature, 450° F (505 K); disk tangential speed, 125 feet per second (38.2 m/sec). Lubricant viscosity at 450° F (505 K); synthetic paraffinic oil, 4.3 centistokes (4.3×10^{-6} m²/sec); advanced ester, 1.2 centistokes (1.2×10^{-6} m²/sec).

Bearing Surface Appearance

All bearings were closely examined after test. Deposit formations, if any, were very light. Those deposits that were apparent, on bearings run at higher oxygen concentrations, were greater with the ester than with the synthetic paraffinic oil (ref. 12) at identical conditions. The inner- and outer-race ball tracks showed no surface damage in any test. This is a further indication that elastohydrodynamic lubrication was the predominant mode of lubrication throughout the range of test conditions.

SUMMARY OF RESULTS

An advanced Type II ester was tested with 204-size angular-contact ball bearings of AISI M-1 steel in a high-temperature bearing test apparatus. The oxygen concentration of the atmosphere within the test bearing chamber was varied from less than 0.1 percent to approximately 21 percent by volume. The effects of the oxygen concentration on the lubricant at temperatures of 400° and 450° F (477 and 505 K) were studied. Test conditions were a thrust load of 70 pounds (310 N) producing a maximum Hertz stress of 200 000 psi (1.38×10^{9} N/m^{2}) at the inner-race-ball contact and an inner-race speed of 10 600 rpm.

1. There was insignificant oxidation of the advanced ester in 6-hour tests at a 400° F (477 K) outer-race temperature up to a 21-percent oxygen concentration. However, at a 21-percent oxygen concentration at 400° F (477 K), a significant increase in oxidation rate occurred after 25 hours of operation suggesting an operating time limitation on the effectiveness of the oxidation inhibitor in the fluid.
2. At 450° F (505 K) a general trend toward increased oxidation of the ester with increased oxygen concentration was noted.
3. The induction period of about 25 hours with the advanced ester at 400° F (477 K) and 21-percent oxygen concentration was much greater than that with a synthetic paraffinic oil which, under these conditions, exhibited a high rate of oxidation within 6 hours.
4. Based on preliminary elastohydrodynamic (EHD) film thickness measurements and post-test bearing surface examination, EHD lubrication was the predominant mode of lubrication throughout the range of test conditions.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 1, 1969,
126-15-02-28-22.

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